

The Radiative Impact of Smoke Aerosols on Clouds in Southeast Asia

N. C. Hsu¹, J. R. Herman², and Si-Chee Tsay³

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Popular Abstract. Every boreal spring the indigenous populations of Laos, Thailand, Vietnam, Burma, and southern China clear the ground needed to plant agricultural crops by setting fires. The smoke aerosols generated from these biomass burning activities are often transported over clouds in the downwind area in the southeastern part of China, resulting in darkened (or browned) color of clouds as seen from space. In this paper, we use satellite data to investigate the impact of smoke aerosols generated from biomass burning activities in Southeast Asia on the total (direct and indirect) reflected solar radiation from clouds. Narrowband measurements from ultra-violet to near-infrared wavelengths (from SeaWiFS and TOMS) were combined with broadband radiation measurements (from CERES). Using this information, we quantified how smoke aerosols change the cloud forcing spectrally and as a whole in the Southeast Asia region. In this region our results show that smoke is present over large areas of cloud-covered regions, and that the frequency of such occurrences is high in the boreal spring. Depending on the thickness of the smoke aerosol, the reflected solar radiation from clouds could be reduced by as much as 100 Watt/m^2 , on average over the March 2000 data. We also found that the reduction in the reflectance of the clouds at 670 nm is large enough to lead to significant errors in cloud optical thickness retrievals from satellites such as AVHRR and MODIS.

¹ GEST, University of Maryland, Baltimore County, 1000 Hilltop Circle, Baltimore, MD 21250

² Goddard Space Flight Center, Code 916, Greenbelt, MD 20771

³ Goddard Space Flight Center, Code 913, Greenbelt, MD 20771

The Radiative Impact of Smoke Aerosols on Clouds in Southeast Asia

N. Christina Hsu¹, Jay R. Herman², and Si-Chee Tsay³

Abstract

The impact of smoke aerosols generated from biomass burning activities in Southeast Asia on the total (direct and indirect) reflected solar radiation from clouds was investigated using satellite data. Narrowband measurements from UV to near-infrared wavelengths (from SeaWiFS and TOMS) were combined with broadband radiation measurements (from CERES). Using this information, we quantified how smoke aerosols change the cloud forcing spectrally and as a whole in the Southeast Asia region. In this region our results show that smoke is present over large areas of cloud-covered regions, and that the frequency of such occurrences is high in the boreal spring. Depending on the thickness of the smoke aerosol, the reflected solar radiation from clouds could be reduced by as much as 100 Watt/m², on average over the March 2000 data. We also found that the reduction in the reflectance of the clouds at 670 nm is large enough to lead to significant errors in cloud optical thickness retrievals from satellites such as AVHRR and MODIS.

¹ GEST, University of Maryland, Baltimore County, 1000 Hilltop Circle, Baltimore, MD 21250. (email: hsu@wrabbit.gsfc.nasa.gov)

² NASA Goddard Space Flight Center, Code 916, Greenbelt, MD 20771. (email: herman@climate.gsfc.nasa.gov)

³ NASA Goddard Space Flight Center, Code 913, Greenbelt, MD 20771. (email: tsay@tparty.gsfc.nasa.gov)

Introduction

Over the last several years, increasing attention has been paid to the effects of tropospheric aerosols on Earth's overall radiation balance [Penner et al., 1997]. Most of this attention has been focused on understanding how aerosols modify the longwave and shortwave radiation budget over cloud-free scenes [Hobbs et al., 1997; Ross et al., 1998]. However, the effects of aerosols on radiative forcing due to clouds are even less well understood than over cloud-free scenes. Since cloud forcing is a much bigger component of the radiation budget, the effect of aerosols over clouds may have an even larger effect on radiative balance compared to aerosol forcing alone.

The Southeast Asia area provides excellent atmospheric conditions to study such effects. Every boreal spring the indigenous populations of Laos, Thailand, Vietnam, Burma, and southern China clear the ground needed to plant agricultural crops by setting fires. While the fires are often set in areas that are relatively dry and that have little cloud cover (particularly in Burma, Thailand, and Laos), the smoke plumes they generate can stretch hundreds of kilometers into areas of heavy cloud cover (Vietnam and southern China). During the spring, this cloud cover is generally composed of stratiform, low-altitude clouds associated with frontal systems that originate in China. Because both smoke and clouds converge over Vietnam and southern China, darkened (brown colored) clouds are often seen in satellite images obtained during this season as smoke gets transported over the low-lying cloud deck.

In this paper, we combine data from three different satellites (SeaWiFS, TOMS, and CERES) to examine how smoke aerosols generated from biomass burning activity in Southeast Asia affect the reflected solar radiation from clouds underneath aerosol plumes.

Satellite Data Sets

While the SeaWiFS instrument was primarily designed to measure ocean color, since its launch in 1997 it has been the major source for providing a comprehensive global data set of such measurements. However, the well-calibrated set of radiances measured in the wavelength range from the visible (0.41 μm) to the near infrared, NIR, (0.87 μm) is also well suited to providing RGB imagery as well as information about atmospheric aerosols [McClain et al., 1998]. There are two types of SeaWiFS data: 1 km resolution (LAC and HRPT) and 4 km resolution (GAC). In this analysis, we use the 4 km resolution level 1 radiance data from SeaWiFS.

Four different TOMS instruments have provided over 20 years of daily global measurements of UV radiances at discrete wavelengths from 312 nm to 380 nm. The data set started in November 1978 and, with the exception of a data gap from January 1995 until August 1996, continues to the present day. While primarily designed to measure total column ozone amounts, TOMS UV measurements can also be used to study tropospheric aerosols through a quantity known as the aerosol index (AI) [Hsu et al., 1996; Herman et al., 1997; Torres et al., 1998], especially for detecting the presence of aerosols

over clouds. In this study, we use AI data from Earth Probe (EP) TOMS (1996 to present). The footprint size for EP TOMS is roughly $40 \times 40 \text{ km}^2$ at nadir.

The CERES instrument is an advanced version of the ERBE instrument and provides radiometric measurements of the Earth's atmosphere from three broadband channels. The CERES data used in this analysis is from the Terra satellite, launched in December 1999. The CERES primary products include shortwave ($0.3\text{--}5 \mu\text{m}$), longwave ($5\text{--}200 \mu\text{m}$), and total radiation ($0.3\text{--}200 \mu\text{m}$) flux [Wielicki et al., 1996]. In order to obtain radiation measurements with the smallest footprint, we use the CERES ES-8 scanner data. The footprint size of CERES scanner measurements is approximately 20 km at nadir.

Example of Smoke-Cloud Conditions in Southeast Asia

To study an example of conditions typically seen over this area in the spring, we looked at the effect of smoke for March 17, 2000. On this day, several large smoke plumes generated from biomass burning were observed in cloud-free conditions over Laos, Thailand, and Burma. Studies of NCEP wind data indicate that the prevailing wind in this region is, in general, westerly for this time of the year, and the smoke was therefore carried to the east. The SeaWiFS RGB image for this day, seen in Figure 1a, clearly shows smoke that has drifted east over a cloudbank located over northern Vietnam and southern China and darkened a significant portion of it.

The TOMS aerosol index image for the same day, seen in Figure 1b, shows enhanced aerosol index values ($\text{AI} > 4$) in the region where smoke is seen over the cloudbank. However, the haze seen over Laos, Thailand, and Burma under cloud-free conditions does not have as high an AI signal, probably because of reduced sensitivity of TOMS AI to absorbing aerosols that are low in the atmosphere and close to the low-reflecting surface. A transect line that crosses from the white cloud to the dirty cloud area has been drawn on both figures. Correspondingly, the CERES top-of-atmosphere (TOA) upwelling shortwave (SW) flux for the same region was shown in Figure 1c.

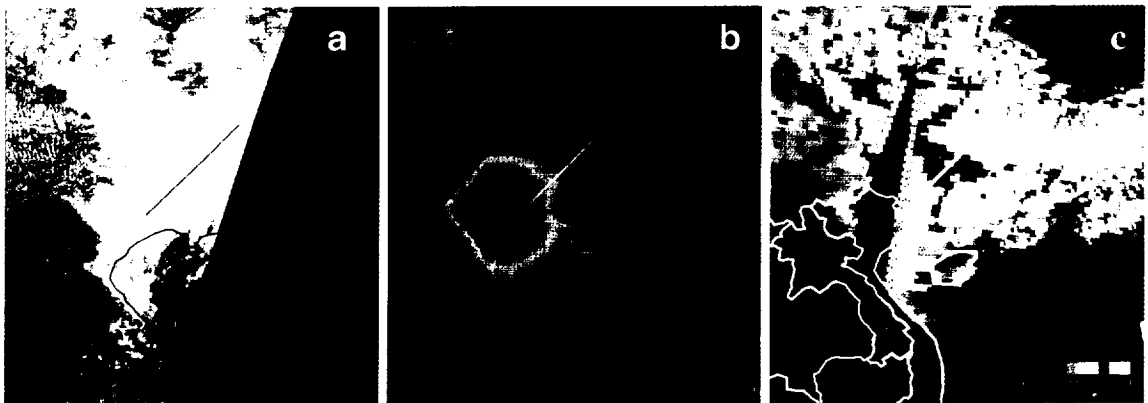


Figure 1: SeaWiFS RGB image for Southeast Asia on March 17, 2000 is shown in (a), the corresponding TOMS AI is shown in (b), and the CERES TOA upwelling shortwave flux is shown in (c).

It is apparent that for overcast conditions the CERES SW flux (Figure 1c) shows a high negative correlation with the TOMS AI (Figure 1b) and the reduced cloud reflectivity in the SeaWiFS RGB image (Figure 1a).

Analysis of Spectral Signature

To examine how the presence of such smoke aerosols changes the overall cloud reflectivity spectrally, we calculate the Lambertian equivalent reflectivity (LER) derived using the SeaWiFS level 1 radiances from the 412nm (blue), 670nm (red), and 865nm (NIR) channels for this region. The radiance at a given wavelength λ , I_λ , can be expressed as a sum of the atmospheric backscatter above a specified Lambertian surface, $I_{0\lambda}$, and the radiance reflected from this surface:

$$I_\lambda = I_{0\lambda}(\theta, \theta_0, P) + \frac{R_\lambda T_\lambda(\theta, \theta_0, P)}{1 - R_\lambda S_b(P)}$$

where S_b is the diffuse reflection of the atmosphere illuminated from below by an isotropic source, θ is the satellite zenith angle, θ_0 is the solar zenith angle, T_λ is the total amount of direct plus diffuse radiation reaching the surface multiplied by the atmospheric transmission of the diffuse reflected radiation in the direction of the satellite, and P is the surface pressure. $I_{0\lambda}$, S_b , and T_λ are calculated using a radiative transfer code.

The LER values (R_{412} , R_{670} , and R_{865}) are shown in Figure 2 (upper panel) as a function of longitude along the transect in Figures 1a, 1b and 1c. The cloud reflectivity from all three channels is seen to decrease from the white-cloud regime in the eastern part of the transect line (longitude $>111^\circ$ E) to the dirty-cloud regime in the western part (longitude $<111^\circ$ E). The reflectivities decrease by approximately 10% (from 90% to 80%) in the 865 nm channel, 20% (from 86% to 70%) in the 670 nm channel, and 30% (from 86% to 60%) in the 412 nm channel. As a result, the spectral dependence of the cloud reflectivity is different over dirty clouds when compared to the much smaller spectral dependence over smoke-free white clouds.

Figure 2 (bottom panel) indicates that the percentage reduction in radiation over the dirty cloud is largest in blue light compared to longer wavelengths. Superimposed in this figure are the corresponding CERES SW fluxes (denoted by green filled circles) on a single pixel resolution along the same transect line. The values of these SW fluxes were seen to decrease significantly from white cloud to dirty cloud, while the values of the TOMS AI (from Figure 1b) increase from near zero to about 3.

Statistical Analysis of Aerosol Effect on Cloud Forcing

In order to investigate the radiative impact of smoke on clouds in this region on a monthly basis, we generated a collocated data set by averaging the daily level 2 data from all three satellites into 0.5° latitude by 0.5° longitude bins for the entire month of March 2000. We then combined SW flux from CERES with AI from TOMS and LER from SeaWiFS for each grid box within the region bounded by the latitudes 15° N - 30° N and

the longitudes 100° E - 125° E. To ensure that the scene is relatively overcast, only data in which the LER derived from the SeaWiFS 865 nm channel, R_{865} , was greater than 70% for smoke-free clouds were included in the analysis. The R_{865} screening criterion for smoke-laden clouds was greater than 60% since, as mentioned earlier, smoke aerosols darken the cloud reflectance slightly at 865 nm. Two histograms were generated from this

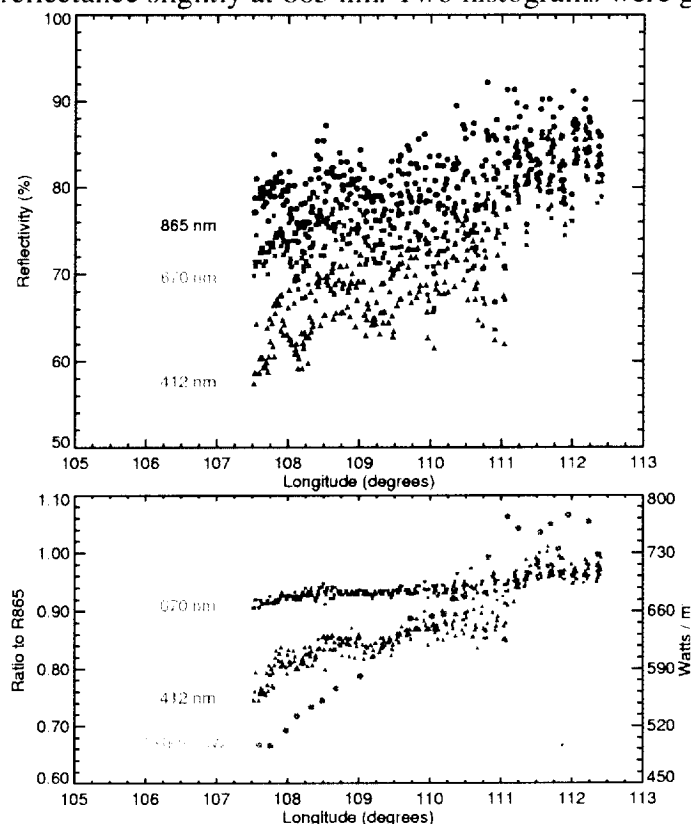


Figure 2: (Upper panel) LER for 865 nm (black), 670 nm (red), and 412 nm (blue) along the transect shown in Figure 1. (Bottom panel) The ratio of the 670 nm and 412 nm LER with respect to 865 nm. The CERES shortwave flux is superimposed with the scale showing on the right Y-axis.

data set; one for relatively smoke-free clouds ($AI < 0.1$) is depicted in Figure 3a and one for smoke-laden clouds ($AI > 1.5$) is depicted in Figure 3b.

For the case of relatively smoke-free clouds, Figure 3a shows that the TOA upwelling SW flux peaks at 720-740 W/m^2 on a monthly average for this region during March. However, in contrast, Figure 3b indicates that, when smoke is observed to be above the cloud, the peak of the TOA SW flux over the cloudy area in the same region during the same season is reduced to about 600-640 W/m^2 . Therefore, the reduction in outgoing SW flux when smoke aerosols occur over cloudy region is substantial.

Concluding Remarks

In this study, we demonstrated that large perturbations in the reflected solar radiation from clouds occur when smoke aerosols are transported over clouds. These perturbations can be 100 W/m^2 or more, and are significantly larger than smoke aerosol

forcing under clear-sky conditions [Hobbs et al., 1997]. Based on model calculations, this aerosol effect can be attributed partly to a direct effect (absorption of sunlight above the cloud) and to an indirect effect (mixing and interacting with low clouds). More ground and aircraft measurements are needed in order to fully understand and separate the contributions from both.

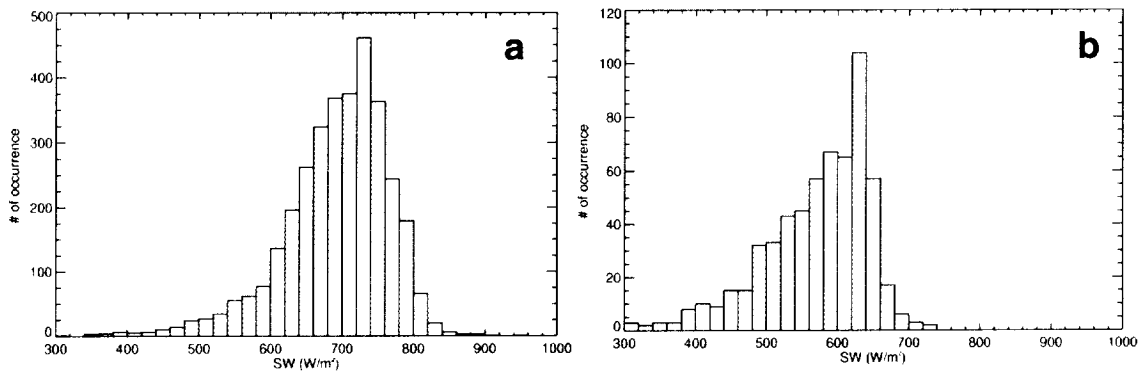


Figure 3: The monthly histograms of the TOA upwelling SW flux for the region of 15°-30° N and 100° - 125° E during March 2000 (a) over smoke free clouds, and (b) for clouds with overlying smoke.

Such large perturbations in radiation could induce a change in the terrestrial heat budget balance that could affect local wind circulation patterns. This, in turn, may lead to changes in the time when the Southeast Asian monsoon begins, currently in the late boreal spring and early summer. Perturbations in the onset of the Southeast Asian monsoon are believed to have great influence on the development of full-scale Asian summer monsoons during the subsequent months [Lau and Yang, 1997].

References

- Herman, J.R., P.K. Bhartia, O.Torres, C. Hsu, C. Seftor, and E. Celarier, Global Distribution of UV-Absorbing Aerosols From Nimbus-7/TOMS Data, *J.Geophys. Res.*, 102, 16,911-16,922, 1997.
- Hsu, N. C., J. R. Herman, P. K. Bhartia, C. J. Seftor, O. Torres, A. M. Thompson, J. F. Gleason, T. F. Eck, and B. N. Holben, Detection of biomass burning smoke from TOMS measurements, *Geophy. Res. Lett.*, 23, 745-748, 1996.
- Hobbs, P. V., J. S. Reid, R. A. Kotchenruther, R. J. Ferek, R. Weiss, Direct radiative forcing by smoke from biomass burning, *Science*, 275, 1776-1778, 1997.
- Lau, K.-M., and S. Yang, Climatology and interannual variability of the Southeast Asian summer monsoon, *Adv. In Atmos. Sci.*, 14, 141-162, 1997.
- McClain, C.R., M.L. Cleave, G.C. Feldman, W.W. Gregg, S.B. Hooker, and N. Kuring, Science quality SeaWiFS data for global biospheric research, *Sea Technol.*, 39, 10-16, 1998.
- Penner, J. E., R. E. Dickinson, and C. A. O'Neill, Effects of aerosol from biomass burning on the global radiation budget, *Science*, 256, 1432-1433, 1992.
- Ross, J. L., P. V. Hobbs, B. Holben, Radiative characteristics of regional hazes dominated by smoke from biomass burning in Brazil: Closure tests and direct radiative forcing, *J. Geophys. Res.*, 103, 31,925-31,941, 1998.

- Torres, O., P. K. Bhartia, J. R. Herman, Z. Ahmad, and J. Gleason, Derivation of aerosol properties from satellite measurements of backscattered ultraviolet radiation. Theoretical basis, *J. Geophys. Res.*, 103, 17099-17110, 1998.
- Wielicki, B. A., B. R. Barkstrom, E. F. Harrison, R. B. Lee III, G. L. Smith, and J. E. Cooper, 1996: Clouds and the Earth's Radiant Energy System (CERES): An Earth Observing System Experiment, *Bull. Amer. Meteor. Soc.*, 77, 853-868.